

METHOD AND APPARATUS FOR DETERMINING SUBSTRATE LAYER THICKNESS  
DURING CHEMICAL MECHANICAL POLISHING

Ins. A1 >

Background

This invention relates generally to chemical mechanical polishing of substrates, and more particularly to a method and apparatus for determining the thickness of a substrate layer during chemical mechanical polishing.

An integrated circuit is typically formed on a substrate by the sequential deposition of conductive, semiconductive or insulative layers on a silicon wafer. After each layer is deposited, the layer is etched to create circuitry features. As a series of layers are sequentially deposited and etched, the outer or uppermost surface of the substrate, i.e., the exposed surface of the substrate, becomes increasingly non-planar. This non-planar surface presents problems in the photolithographic steps of the integrated circuit fabrication process. Therefore, there is a need to periodically planarize the substrate surface.

Chemical mechanical polishing (CMP) is one accepted method of planarization. This planarization method typically requires that the substrate be mounted on a carrier or polishing head. The exposed surface of the substrate is placed against a rotating polishing pad. The polishing pad may be either a "standard" pad or a fixed-abrasive pad. A standard pad has a durable roughened surface, whereas a fixed-abrasive pad has abrasive particles held in a containment media. The carrier head provides a controllable load, i.e., pressure, on the substrate to push it against the polishing pad. A polishing slurry, including at least one chemically-reactive agent, and abrasive particles if a standard pad is used, is supplied to the surface of the polishing pad.

The effectiveness of a CMP process may be measured by its polishing rate, and by the resulting finish (absence of small-scale roughness) and flatness (absence of large-scale topography) of the substrate surface. The polishing rate, finish and flatness are determined by the pad and slurry combination, the

carrier head configuration, the relative speed between the substrate and pad, and the force pressing the substrate against the pad.

In order to determine the effectiveness of different polishing tools and processes, a so-called "blank" wafer, i.e., a wafer with one or more layers but no pattern, is polished in a tool/process qualification step. After polishing, the remaining layer thickness is measured at several points on the substrate surface. The variations in layer thickness provide a measure of the wafer surface uniformity, and a measure of the relative polishing rates in different regions of the substrate. One approach to determining the substrate layer thickness and polishing uniformity is to remove the substrate from the polishing apparatus and examine it. For example, the substrate may be transferred to a metrology station where the thickness of the substrate layer is measured, e.g., with an ellipsometer. Unfortunately, this process can be time-consuming and thus costly, and the metrology equipment is costly.

One problem in CMP is determining whether the polishing process is complete, i.e., whether a substrate layer has been planarized to a desired flatness or thickness. Variations in the initial thickness of the substrate layer, the slurry composition, the polishing pad material and condition, the relative speed between the polishing pad and the substrate, and the load of the substrate on the polishing pad can cause variations in the material removal rate. These variations cause variations in the time needed to reach the polishing endpoint. Therefore, the polishing endpoint cannot be determined merely as a function of polishing time.

One approach to determining the polishing endpoint is to remove the substrate from the polishing surface and examine it. If the substrate does not meet the desired specifications, it is reloaded into the CMP apparatus for further processing. Alternatively, the examination might reveal that an excess amount of material has been removed, rendering the substrate unusable.

There is, therefore, a need for a method of detecting, in-situ, when the desired flatness or thickness had been achieved.

Several methods have been developed for in-situ polishing endpoint detection. Most of these methods involve monitoring a parameter associated with the substrate surface, and indicating an endpoint when the parameter abruptly changes. For example, where an insulative or dielectric layer is being polished to expose an underlying metal layer, the coefficient of friction and the reflectivity of the substrate will change abruptly when the metal layer is exposed.

In an ideal system where the monitored parameter changes abruptly at the polishing endpoint, such endpoint detection methods are acceptable. However, as the substrate is being polished, the polishing pad condition and the slurry composition at the pad-substrate interface may change. Such changes may mask the exposure of an underlying layer, or they may imitate an endpoint condition. Additionally, such endpoint detection methods will not work if only planarization is being performed, if the underlying layer is to be over-polished, or if the underlying layer and the overlying layer have similar physical properties.

In view of the foregoing, there is a need for a polishing endpoint detector which more accurately and reliably determines when to stop the polishing process. There is also a need for an means for in-situ determination of the thickness of a layer on a substrate during a CMP process.

### Summary

The present invention relates to in-situ optical monitoring of a substrate during chemical mechanical polishing. The thickness of a layer in the substrate can be measured, and the thickness determination may be used to determine an endpoint of the CMP process, determine the thickness of a film remaining on the wafer during the CMP process, and determine thickness of material removed from a wafer in the CMP process.

In one aspect, the invention is directed to an apparatus for chemical mechanical polishing a substrate having a first surface and a second surface underlying the first surface. The apparatus has a first optical system, a second optical system, and a processor. The first optical system includes a first light source to generate a first light beam to impinge on the substrate, the first light beam having a first effective wavelength, and a first sensor to measure light from the first light beam that is reflected from the first and second surfaces to generate a first interference signal. The second optical system includes a second light source to generate a second light beam that impinges the substrate, the second light beam having a second effective wavelength that differs from the first effective wavelength, and a second sensor to measure light from the second light beam that is reflected from the first and second surfaces to generate a second interference signal. The processor is configured to determine a thickness from the first and second interference signals.

Implementations of the invention may include the following, the first and second light beams may have different wavelengths or different incidence angles on the substrate. The first effective wavelength may be greater than the second effective wavelength without being an integer multiple of the second effective wavelength. Each optical system may be an off-axis or an on-axis optical system. At least one of the first and second light sources may include a light emitting diode. The first light source may be a first light emitting diode with a first coherence length and the second light source may be a second light emitting diode having a second coherence length. The first coherence length may be greater than an optical path length of the first light beam through the surface layer, and the second coherence length may be greater than an optical path length of the second light beam through the surface layer. The apparatus may have a polishing pad which contacts the first surface of the substrate during polishing and a platen to support the polishing

pad. The platen may include an aperture through which the first and second light beams pass, or the platen may include a first aperture through which the first light beam passes and a second aperture through which the second light beam passes. The  
5 polishing pad may include a transparent window through which the first and second light beams pass, or the polishing pad may include a first window through which the first light beam passes and a second window through which the second light beam passes. The first light beam may have a first wavelength, e.g., between  
10 about 600 and 1500 nanometers, and the second light beam may have a second wavelength, e.g., between about 300 and 600 nanometers, that is shorter than the first wavelength. The first light beam may have an incidence angle on the substrate that is less than a second incidence angle of the second light beam on the substrate.

15 The processor may be configured to determine an initial thickness during polishing of the substrate. The processor may be configured to determine a first model intensity function for the first interference signal and a second model intensity function for the second interference signal. The first and  
20 second model intensity functions may be sinusoidal functions, e.g., described by a first period and a first phase offset and a second period and a second phase offset, respectively. The first period and the first phase offset may be computed from a least square fit of the first model intensity function to intensity  
25 measurements from the first interference signal, and the second period and the second phase offset may be computed from a least square fit of the second model function intensity to intensity measurements from the second interference signal. The thickness may be estimated by a first model thickness function which is a  
30 function of a first integer, the first effective wavelength, the first period and the first phase offset, and by a second model thickness function which is a function of a second integer, the second effective wavelength, the second period and the second phase offset. The processor is configured to determine a first  
35 value for the first integer and a second value for the second

integer which provide approximately equal estimates of the thickness from the first and second model thickness functions. The processor may be configured to determine the first and second values by finding solutions to the equation:

$$M = \left( \frac{\phi_2}{\Delta T_2} + N \right) \cdot \frac{\lambda_{eff2}}{\lambda_{eff1}} - \frac{\phi_1}{\Delta T_1}$$

5 where M is the first integer, N is the second integer,  $\lambda_{eff1}$  is the first effective wavelength,  $\lambda_{eff2}$  is the second effective wavelength,  $\Delta T_1$  is the first period,  $\Delta T_2$  is the second period,  $\phi_1$  is the first phase offset, and  $\phi_2$  is the second phase offset.

10 In another aspect, the invention is directed to an apparatus for use in chemical mechanical polishing a substrate having a first surface and a second surface underlying the first surface. The apparatus has a first optical system including a first light source to generate a first light beam to impinge on the substrate, and a first sensor to measure light from the first  
15 light beam that is reflected from the first and second surfaces to generate a first interference signal, and a second optical system including a second light source to generate a second light beam that impinges the substrate, and a second sensor to measure light from the second light beam that is reflected from the first  
20 and second surfaces to generate a second interference signal. The first light beam has a first effective wavelength and the second light beam has a second effective wavelength which differs from the first effective wavelength.

25 In another aspect, the invention is directed to an apparatus for use in chemical mechanical polishing a substrate having a first surface and a second surface underlying the first surface. The apparatus has a first optical system and a second optical system. The first optical system includes a first light emitting diode to generate a first light beam that impinges the substrate,  
30 and a first sensor to measure light from the first light beam that is reflected from the first and second surfaces to generate a first interference signal. The second optical system includes

a second light emitting diode to generate a second light beam that impinges the substrate, and a second sensor to measure light from the second light beam that is reflected from the inner and outer surfaces to generate a second interference signal. The first light beam has a first effective wavelength, and the second light beam has a second effective wavelength that differs from the first effective wavelength.

Implementations of the invention may include the following. The first light beam may have a first wavelength, e.g., between about 700 and 1500 nanometers, and the second light beam may have a second wavelength, e.g., between about 300 and 700 nanometers, that is shorter than the first wavelength. The substrate may have a layer in a thin film structure disposed over a wafer, and the first and second light beams may have coherence lengths sufficiently large to maintain coherence of the first and second light beams as they pass through the layer.

In another aspect, the invention is directed to an apparatus for detecting a polishing endpoint during chemical mechanical polishing of a substrate having a layer disposed over a wafer, the substrate having a first surface and a second surface underlying the first surface. The apparatus has a light emitting diode to generate a light beam that impinges the layer of the substrate, a sensor to measure light from the light beam that is reflected from the first and second surfaces to generate an interference signal, and a processor configured to determine an polishing endpoint from the interference signal. The light beam emitted by the light emitting diode has a coherence length equal to or greater than the optical path length of the light beam through the layer.

In yet another aspect, the invention is directed to an endpoint detector for use in chemical mechanical polishing a substrate having a layer in a thin film structure disposed over a wafer. The substrate has has a first surface and a second surface underlying the first surface. The endpoint detector has a first optical system, a second optical system, and a processor.

The first optical system includes a first light source to generate a first light beam that impinges the substrate, and a first sensor to measure light from the first light beam that is reflected from the inner and outer surfaces to generate a first interference signal. The second optical system includes a second light source to generate a second light beam that impinges the substrate, and a second sensor to measure light from the second light beam that is reflected from the inner and outer surfaces to generate a second interference signal. The first light beam has a first effective wavelength, and the second light beam has a second effective wavelength that differs from the first effective wavelength. The processor is configured to compare the first and second interference signals and detect the polishing endpoint.

In yet another aspect, the invention is directed to an apparatus for determining a thickness during chemical mechanical polishing of a substrate having a first surface and a second surface underlying the first surface. The apparatus has means for generating first and second light beams having different effective wavelengths to impinge on the substrate, means for detecting light from the first and second light beams that is reflected from the first and second surfaces to generate a first and second interference signals, and means for determining a thickness from the first and second interference signals.

In yet another aspect, the invention is directed to an apparatus for measuring a thickness during chemical mechanical polishing of a substrate having a first surface and a second surface underlying the first surface. The apparatus has means for generating first and second light beams having different effective wavelengths to impinge on the substrate, means for detecting light from the first and second light beams that is reflected from the first and second surfaces to generate a first and second interference signals, and means for determining a thickness from the first and second interference signals.

In still another aspect, the invention is directed to a method of determining a thickness in a substrate undergoing



chemical mechanical polishing. A first interference signal is generated by directing a first light beam having a first effective wavelength onto the substrate and measuring light from the first light beam reflected from the substrate, and a second interference signal is generated by directing a second light beam having a second effective wavelength onto the substrate and measuring light from the second light beam reflected from the substrate. The first effective wavelength differs from the second effective wavelength. The thickness is determined from the first and second interference signals.

Implementations of the method may include the following. First and second model intensity functions may be determined for the first and second interference signals. The first and second model intensity functions are sinusoidal functions, and may each be described by a period and a phase offset. The period and offset of each model intensity function may be computed from a least square fit of the model intensity function to the intensity measurements from the interference signal. The thickness may be estimated by a first model thickness function which is a function of a first integer, the first effective wavelength, the first period and the first phase offset, and by a second model thickness function which is a function of a second integer, the second effective wavelength, the second period and the second phase offset. A first value for the first integer and a second value for the second integer may be determined which provide approximately equal estimates of the thickness from the first and second model thickness functions. Determining the first and second value may include finding solutions to the equation

$$M = \left( \frac{\phi_2}{\Delta T_2} + N \right) \cdot \frac{\lambda_{eff2}}{\lambda_{eff1}} - \frac{\phi_1}{\Delta T_1}$$

where M is the first integer, N is the second integer,  $\lambda_{eff1}$  is the first effective wavelength,  $\lambda_{eff2}$  is the second effective wavelength,  $\Delta T_1$  is the first period,  $\Delta T_2$  is the second period,  $\phi_1$  is the first phase offset, and  $\phi_2$  is the second phase offset.

The first and second light beams have different wavelengths or different incidence angles on the substrate.

In still another aspect, the invention is directed to a method of detecting a polishing endpoint during polishing of a substrate. A first interference signal is generated by directing a first light beam having a first effective wavelength onto the substrate and measuring light from the first light beam reflected from the substrate, and a second interference signal is generating by directing a second light beam having a second effective wavelength onto the substrate and measuring light from the second light beam reflected from the substrate. The first effective wavelength differs from the second effective wavelength. The first and second interference signals are compared to determine the polishing endpoint.

Advantages of the invention include the following. With two optical systems, an estimate of the initial and remaining thickness of the layer on the substrate can be generated. Employing two optical systems operating at different effective wavelengths also allows more accurate determination of parameters that were previously obtained with a single optical system.

Other features and advantages of the invention will become apparent from the following description, including the drawings and claims.

#### Brief Description of the Drawings

FIG. 1 is a schematic exploded perspective view of a CMP apparatus according to the present invention.

FIG. 2 is schematic view, in partial section, of a polishing station from the CMP apparatus of FIG. 1 with two optical systems for interferometric measurements of a substrate.

FIG. 3 is a schematic top view of a polishing station from the CMP apparatus of FIG. 1.

FIG. 4 is a schematic diagram illustrating a light beam from the first optical system impinging a substrate at an angle and reflecting from two surfaces of the substrate.

FIG. 5 is a schematic diagram illustrating a light beam from the second optical system impinging a substrate at an angle and reflecting from two surfaces of the substrate.

FIG. 6 is a graph of a hypothetical reflective trace that could be generated by the first optical system in the CMP apparatus of FIG. 2.

FIG. 7 is a graph of a hypothetical reflectance trace that could be generated by the second optical system in the CMP apparatus of FIG. 2.

FIGS. 8A and 8B are graphs of two hypothetical model functions.

FIG. 9 is a schematic cross-sectional view of a CMP apparatus having a first, off-axis optical system and a second, normal-axis optical system.

FIG. 10 is a schematic diagram illustrating a light beam impinging a substrate at a normal incidence and reflecting from two surfaces of the substrate.

FIG. 11 is a schematic cross-sectional view of a CMP apparatus having a two optical systems and one window in the polishing pad.

FIG. 12 is a schematic cross-sectional view of a CMP apparatus having two off-axis optical systems and one window in the polishing pad.

FIG. 13 is a schematic cross-sectional view of a CMP apparatus having two optical modules arranged alongside each other.

FIGS. 14 and 15 are unfiltered and filtered reflectivity traces, respectively, generated using a light emitting diode with a peak emission at 470nm.

#### Detailed Description

Referring to FIGS. 1 and 2, one or more substrates 10 will be polished by a chemical mechanical polishing (CMP) apparatus 20. A description of a similar polishing apparatus may be found in U.S. Patent No. 5,738,574, the entire disclosure of which is

incorporated herein by reference. Polishing apparatus 20 includes a series of polishing stations 22 and a transfer station 23. Transfer station 23 serves multiple functions, including receiving individual substrates 10 from a loading apparatus (not shown), washing the substrates, loading the substrates into carrier heads, receiving the substrates from the carrier heads, washing the substrates again, and finally, transferring the substrates back to the loading apparatus.

Each polishing station includes a rotatable platen 24 on which is placed a polishing pad 30. The first and second stations may include a two-layer polishing pad with a hard durable outer surface, whereas the final polishing station may include a relatively soft pad. If substrate 10 is an "eight-inch" (200 millimeter) or "twelve-inch" (300 millimeter) diameter disk, then the platens and polishing pads will be about twenty inches or thirty inches in diameter, respectively. Each platen 24 may be connected to a platen drive motor (not shown). For most polishing processes, the platen drive motor rotates platen 24 at thirty to two hundred revolutions per minute, although lower or higher rotational speeds may be used. Each polishing station may also include a pad conditioner apparatus 28 to maintain the condition of the polishing pad so that it will effectively polish substrates.

Polishing pad 30 typically has a backing layer 32 which abuts the surface of platen 24 and a covering layer 34 which is used to polish substrate 10. Covering layer 34 is typically harder than backing layer 32. However, some pads have only a covering layer and no backing layer. Covering layer 34 may be composed of an open cell foamed polyurethane or a sheet of polyurethane with a grooved surface. Backing layer 32 may be composed of compressed felt fibers leached with urethane. A two-layer polishing pad, with the covering layer composed of IC-1000 and the backing layer composed of SUBA-4, is available from Rodel, Inc., of Newark, Delaware (IC-1000 and SUBA-4 are product names of Rodel, Inc.).

A slurry 36 containing a reactive agent (e.g., deionized water for oxide polishing) and a chemically-reactive catalyzer (e.g., potassium hydroxide for oxide polishing) may be supplied to the surface of polishing pad 30 by a slurry supply port or combined slurry/rinse arm 38. If polishing pad 30 is a standard pad, slurry 36 may also include abrasive particles (e.g., silicon dioxide for oxide polishing).

A rotatable carousel 40 with four carrier heads 50 is supported above the polishing stations by a center post 42. A carousel motor assembly (not shown) rotates center post 42 to orbit the carrier heads and the substrates attached thereto between the polishing and transfer stations. A carrier drive shaft 44 connects a carrier head rotation motor 46 (see FIG. 2) to each carrier head 50 so that each carrier head can independently rotate about its own axis. In addition, a slider (not shown) supports each drive shaft in an associated radial slot 48. A radial drive motor (not shown) may move the slider to laterally oscillate the carrier head. In operation, the platen is rotated about its central axis 25, and the carrier head is rotated about its central axis 51 and translated laterally across the surface of the polishing pad.

The carrier head 50 performs several mechanical functions. Generally, the carrier head holds the substrate against the polishing pad, evenly distributes a downward pressure across the back surface of the substrate, transfers torque from the drive shaft to the substrate, and ensures that the substrate does not slip out from beneath the carrier head during polishing operations. A description of a carrier head may be found in U.S. Patent Application Serial No. 08/861,260, entitled a CARRIER HEAD WITH a FLEXIBLE MEMBRANE FOR a CHEMICAL MECHANICAL POLISHING SYSTEM, filed May 21, 1997, by Steven M. Zuniga et al., assigned to the assignee of the present invention, the entire disclosure of which is incorporated herein by reference.

Referring to FIGS. 2 and 3, two holes or apertures 60 and 80 are formed in platen 24, and two transparent windows 62 and 82

are formed in polishing pad 30 overlying holes 60 and 80, respectively. The holes 60 and 80 may be formed on opposite sides of platen 24, e.g., about 180° apart. Similarly, windows 62 and 82 may be formed on opposite sides of polishing pad 30 over holes 60 and 80, respectively. Transparent windows 62 and 82 may be constructed as described in U.S. Patent Application Serial No. 08/689,930, entitled METHOD OF FORMING A TRANSPARENT WINDOW IN A POLISHING PAD FOR A CHEMICAL MECHANICAL POLISHING APPARATUS by Manoocher Birang, et al., filed August 26, 1996, and assigned to the assignee of the present invention, the entire disclosure of which is incorporated herein by reference. Holes 60, 80 and transparent windows 62, 82, are positioned such that they each alternately provide a view of substrate 10 during a portion of the platen's rotation, regardless of the translational position of carrier head 50.

Two optical systems 64 and 84 for interferometric measurement of the substrate thickness and polishing rate are located below platen 24 beneath windows 62 and 82, respectively. The optical systems may be secured to platen 24 so that they rotate with the platen and thereby maintain a fixed position relative to the windows. The first optical system is an "off-axis" system in which light impinges the substrate at a non-normal incidence angel. Optical system 64 includes a first light source 66 and a first sensor 68, such as a photodetector. The first light source 66 generates a first light beam 70 which propagates through transparent window 62 and any slurry 36 on the pad (see FIG. 4) to impinge the exposed surface of substrate 10. The light beam 70 is projected from light source 66 at an angle  $\alpha_1$  from an axis normal to the surface of substrate 10. The propagation angle  $\alpha_1$  may be between 0° and 45°, e.g., about 16°. In one implementation, light source 66 is a laser that generates a laser beam with a wavelength of about 600-1500 nanometers (nm), e.g., 670 nm. If hole 60 and window 62 are elongated, a beam expander (not illustrated) may be positioned in the path of light beam 70 to expand the light beam along the elongated axis of the

window.

The second optical system 84 may also be an "off-axis" optical system with a second light source 86 and a second sensor 88. The second light source 86 generates a second light beam 90 which has a second wavelength that is different from the first wavelength of first light beam 70. Specifically, the wavelength of the second light beam 90 may be shorter than the wavelength of the first light beam 70. In one implementation, second light source 86 is a laser that generates a light beam with a wavelength of about 300-500 nm or 300-600 nm, e.g., 470 nm. The light beam 90 is projected from light source 86 at an angle of  $\alpha_2$  from an axis normal to the exposed surface of the substrate. The projection angle  $\alpha_2$  may be between 0° and 45°, e.g., about 16°. If the hole 80 and window 82 are elongated, another beam expander (not illustrated) may be positioned in the path of light beam 90 to expand the light beam along the elongated axis of the window.

Light sources 66 and 86 may operate continuously. Alternately, light source 66 may be activated to generate light beam 70 when window 62 is generally adjacent substrate 10, and light source 86 may be activated to generate light beam 90 when window 82 is generally adjacent substrate 10.

The CMP apparatus 20 may include a position sensor 160, to sense when windows 62 and 82 are near the substrate. Since platen 24 rotates during the CMP process, platen windows 62 and 82 will only have a view of substrate 10 during part of the rotation of platen 24. To prevent spurious reflections from the slurry or the retaining ring from interfering with the interferometric signal, the detection signals from optical systems 64, 84 may be sampled only when substrate 10 is impinged by one of light beams 70, 90. The position sensor is used to ensure that the detection signals are sampled only when substrate 10 overlies one of the windows. Any well known proximity sensor could be used, such as a Hall effect, eddy current, optical interrupter, or acoustic sensor. Specifically, position sensor 160 may include two optical interrupters 162 and 164 (e.g.,

LED/photodiode pairs) mounted at fixed points on the chassis of the CMP apparatus, e.g., opposite each other and 90° from carrier head 50. A position flag 166 is attached to the periphery of the platen. The point of attachment and length of flag 166, and the positions of optical interrupters 162 and 164, are selected so that the flag triggers optical interrupter 162 when window 62 sweeps beneath substrate 10, and the flag triggers optical interrupter 164 when window 82 sweeps beneath substrate 10. The output signal from detector 68 may be measured and stored while optical interrupter 162 is triggered by the flag, and the output signal from detector 88 may be measured and stored while optical interrupter 164 is triggered the flag. The use of a position sensor is also discussed in the above-mentioned U.S. Patent Application Serial No. 08/689,930.

In operation, CMP apparatus 20 uses optical systems 64, 84 to determine the amount of material removed from the surface of the substrate, or to determine when the surface has become planarized. The light source 66, 86, detectors 68, 88 and sensor 160 may be connected to a general purpose programmable digital computer or processor 52. A rotary coupling 56 may provide electrical connections for power and data to and from light sources 66, 86 and detectors 68, 88. Computer 52 may be programmed to receive input signals from the optical interrupter, to store intensity measurements from the detectors, to display the intensity measurements on an output device 54, to calculate the initial thickness, polishing rate, amount removed and remaining thickness from the intensity measurements, and to detect the polishing endpoint.

Referring to FIG. 4, substrate 10 includes a wafer 12, such as a silicon wafer, and an overlying thin film structure 14. The thin film structure includes a transparent or partially transparent outer layer, such as a dielectric layer, e.g., an oxide layer, and may also include one or more underlying layers, which may be transparent, partially transparent, or reflective.

At the first optical system 64, the portion of light beam 70



which impinges on substrate 10 will be partially reflected at a first surface, i.e., the surface of the outer layer, of thin film structure 14 to form a first reflected beam 74. However, a portion of the light will also be transmitted through thin film structure 14 to form a transmitted beam 76. At least some of the light from transmitted beam 76 will be reflected by one or more underlying surfaces, e.g., by one or more of the surfaces of the underlying layers in structure 14 and/or by the surface of wafer 12, to form a second reflected beam 78. The first and second reflected beams 74, 78 interfere with each other constructively or destructively depending on their phase relationship, to form a resultant return beam 72 (see also FIG. 2). The phase relationship of the reflected beams is primarily a function of the index of refraction and thickness of the layer or layers in thin film structure 14, the wavelength of light beam 70, and the angle of incidence  $\alpha_1$ .

Returning to FIG. 2, return beam 72 propagates back through slurry 36 and transparent window 62 to detector 68. If the reflected beams 74, 78 are in phase with each other, they cause a maxima ( $I_{\max 1}$ ) on detector 68. On the other hand, if reflected beams 74, 78 are out of phase, they cause a minima ( $I_{\min 1}$ ) on detector 68. Other phase relationships will result in an interference signal between the maxima and minima being seen by detector 68. The result is a signal output from detector 68 that varies with the thickness of the layer or layers in structure 14.

Because the thickness of the layer or layers in structure 14 change with time as the substrate is polished, the signal output from detector 68 also varies over time. The time varying output of detector 68 may be referred to as an in-situ reflectance measurement trace (or "reflectance trace"). This reflectance trace may be used for a variety of purposes, including detecting a polishing endpoint, characterizing the CMP process, and sensing whether the CMP apparatus is operating properly.

Referring to FIG. 5, in the second optical system 84, a first portion of light beam 90 will be partially reflected by the

surface layer of thin film structure 14 to form a first reflected beam 94. A second portion of the light beam will be transmitted through thin film structure 14 to form a transmitted beam 96. At least some of the light from transmitted beam 96 is reflected, e.g., by one of the underlying layers in structure 14 or by wafer 12, to form a second reflected beam 98. The first and second reflected beams 94, 98 interfere with each other constructively or destructively depending on their phase relationship, to form a resultant return beam 92 (see also FIG. 2). The phase relationship of the reflected beams is a function of the index of refraction and thickness of the layer or layers in structure 14, the wavelength of light beam 90, and the angle of incidence  $\alpha_2$ .

The resultant return beam 92 propagates back through slurry 36 and transparent window 82 to detector 88. The time-varying phase relationship between reflected beams 94, 98 will create a time-varying interference pattern of minima ( $I_{\min 2}$ ) and maxima ( $I_{\max 2}$ ) at detector 88 related to the time-varying thickness of the layer or layers in thin film structure 14. Thus, the signal output from detector 88 also varies with the thickness of the layer or layers in thin film structure 14 to create a second reflectance trace. Because the optical systems employ light beams that have different wavelengths, the time varying reflectance trace of each optical system will have a different pattern.

When a blank substrate, i.e., a substrate in which the layer or layers in thin film structure 14 are unpatterned, is being polished, the data signal output by detectors 68, 88 are cyclical due to interference between the portion of the light beam reflected from the surface layer of the thin film structure and the portion of the light beam reflected from the underlying layer or layers of thin film structure 14 or from wafer 12. Accordingly, the thickness of material removed during the CMP process can be determined by counting the cycles (or fractions of cycles) of the data signal, computing how much material would be removed per cycle (see Equation 5 below), and computing the

product of the cycle count and the thickness removed per cycle. This number can be compared with a desired thickness to be removed and the process controlled based on the comparison. The calculation of the amount of material removed from the substrate is also discussed in the above-mentioned U.S. Patent Application Serial No. 08/689,930.

Referring to FIGS. 6 and 7, assuming that substrate 10 is a "blank" substrate, the resulting reflectance traces 100 and 110 (shown by the dots) from optical systems 64 and 84, respectively, will be a series of intensity measurements that generally follow sinusoidal curves. The CMP apparatus uses reflectance traces 100 and 110 to determine the amount of material removed from the surface of a substrate.

Computer 52 uses the intensity measurements from detectors 68 and 88 to generate a model function (shown by phantom lines 120 and 130) for each reflectance trace 100 and 110. Preferably, each model function is a sinusoidal wave. Specifically, the model function  $I_1(T_{\text{measure}})$  for reflectance trace 100 may be the following:

$$I_1(T_{\text{measure}}) = k_1 \cdot \frac{I_{\text{max}1} + I_{\text{min}1}}{2} + \frac{I_{\text{max}1} - I_{\text{min}1}}{2} \cdot \cos\left(\frac{\phi_1 + T_{\text{measure}}}{\Delta T_1} 2\pi\right) \quad (3)$$

where  $I_{\text{max}1}$  and  $I_{\text{min}1}$  are the maximum and minimum amplitudes of the sine wave,  $\phi_1$  is a phase difference of model function 120,  $\Delta T_1$  is the peak-to-peak period of the sine wave of model function 120,  $T_{\text{measure}}$  is the measurement time, and  $k_1$  is an amplitude adjustment coefficient. The maximum amplitude  $I_{\text{max}1}$  and the minimum amplitude  $I_{\text{min}1}$  may be determined by selecting the maximum and minimum intensity measurements from reflectance trace 100. The model function 120 is fit to the observed intensity measurements of reflectivity trace 100 by a fitting process, e.g., by a conventional least square fit. The phase difference  $\phi_1$  and peak-to-peak period  $\Delta T_1$  are the fitting coefficients to be optimized in Equation 1. The amplitude adjustment coefficient  $k_1$  may be set by the user to improve the fitting process, and may have a

value of about 0.9.

Similarly, the model function  $I_2(T_{\text{measure}})$  for reflectance trace 110 may be the following:

$$I_2(T_{\text{measure}}) = k_2 \cdot \frac{I_{\text{max}2} + I_{\text{min}2}}{2} + \frac{I_{\text{max}2} - I_{\text{min}2}}{2} \cdot \cos\left(\frac{\phi_2 + T_{\text{measure}}}{\Delta T_2} 2\pi\right) \quad (4)$$

where  $I_{\text{max}2}$  and  $I_{\text{min}2}$  are the maximum and minimum amplitudes of the sine wave,  $\phi_2$  is a phase difference of model function 130,  $\Delta T_2$  is the peak-to-peak period of the sine wave of model function 130,  $T_{\text{measure}}$  is the measurement time, and  $k_2$  is an amplitude adjustment coefficient. The maximum amplitude  $I_{\text{max}2}$  and the minimum amplitude  $I_{\text{min}2}$  may be determined by selecting the maximum and minimum intensity measurements from reflectivity trace 110. The model function 130 is fit to the observed intensity measurements of reflectivity trace 110 by a fitting process, e.g., by a conventional least square fit. The phase difference  $\phi_2$  and peak-to-peak period  $\Delta T_2$  are the fitting coefficients to be optimized in Equation 2. The amplitude adjustment coefficient  $k_2$  may be set by the user to improve the fitting process, and may have a value of about 0.9.

Since the actual polishing rate can change during the polishing process, the polishing variables which are used to calculate the estimated polishing rate, such as the peak-to-peak period, should be periodically recalculated. For example, the peak-to-peak periods  $\Delta T_1$  and  $\Delta T_2$  may be recalculated based on the intensity measurements for each cycle. The peak-to-peak periods may be calculated from intensity measurements in overlapping time periods. For example, a first peak-to-peak period may be calculated from the intensity measurement in the first 60% of the polishing run, and a second peak-to-peak period may be calculated from the intensity measurements in the last 60% of the polishing run. The phase differences  $\phi_1$  and  $\phi_2$  are typically calculated only for the first cycle.

Once the fitting coefficients have been determined, the initial thickness of the thin film layer, the current polishing

rate, the amount of material removed, and the remaining thin film layer thickness may be calculated. The current polishing rate  $P$  may be calculated from the following equation:

$$P = \frac{\lambda}{\Delta T \cdot 2n_{\text{layer}} \cos \alpha'} \quad (5)$$

where  $\lambda$  is the wavelength of the laser beam,  $n_{\text{layer}}$  is the index of refraction of the thin film layer, and  $\alpha'$  is the angle of laser beam through the thin film layer, and  $\Delta T$  is the most recently calculated peak-to-peak period. The angle  $\alpha'$  may be determined from Snell's law,  $n_{\text{layer}} \sin \alpha' = n_{\text{air}} \sin \alpha$ , where  $n_{\text{layer}}$  is the index of refraction of the layer in structure 14,  $n_{\text{air}}$  is the index of refraction of air, and  $\alpha$  ( $\alpha_1$  or  $\alpha_2$ ) is the off-vertical angle of light beam 70 or 90. The polishing rate may be calculated from each reflectance trace and compared.

The amount of material removed,  $D_{\text{removed}}$ , may be calculated either from the polishing rate, i.e.,

$$D_{\text{removed}} = P \cdot T_{\text{measure}} \quad (6)$$

or by counting the number or fractional number of peaks in one of the reflectivity trace, and multiplying the number of peaks by the peak-to-peak thickness  $\Delta D$  for that reflective trace (i.e.,  $\Delta D_1$  for reflectance trace 100 and  $\Delta D_2$  for reflectance trace 110), where

$$\Delta D = \frac{\lambda}{2n_{\text{layer}} \cos \alpha'} \quad (7)$$

The initial thickness  $D_{\text{initial}}$  of the thin film layer may be calculated from the phase differences  $\phi_1$  and  $\phi_2$ . The initial thickness  $D_{\text{initial}}$  will be equal to:

$$D_{\text{initial}} = \left( \frac{\phi_1}{\Delta T_1} + M \right) \cdot \frac{\lambda_1}{2n_{\text{layer}} \cos \alpha'_1} \quad (8)$$

and equal to

$$D_{initial} = \left( \frac{\phi_2}{\Delta T_2} + N \right) \cdot \frac{\lambda_2}{2n_{layer} \cos \alpha'_2} \quad (9)$$

where M and N are equal to or close to integer values.

Consequently,

$$M = \left( \frac{\phi_2}{\Delta T_2} + N \right) \cdot \frac{\cos \alpha'_1}{\cos \alpha'_2} \cdot \frac{\lambda_2}{\lambda_1} - \frac{\phi_1}{\Delta T_1} \quad (10)$$

For an actual substrate, the manufacturer will know that the layers in structure 14 will not be fabricated with a thickness greater than some benchmark value. Therefore, the initial thickness  $D_{initial}$  should be less than a maximum thickness  $D_{max}$ , e.g., 25000Å for a layer of silicon oxide. The maximum value,  $N_{max}$ , of N can be calculated from the maximum thickness  $D_{max}$  and the peak-to-peak thickness  $\Delta D_2$  as follows:

$$N_{max} = \frac{D_{max}}{\Delta D_2} = \frac{D_{max} \cdot 2n_{layer} \cos \alpha'_2}{\lambda_2} \quad (11)$$

Consequently, the value of M may be calculated for each integer value of  $N = 1, 2, 3, \dots, N_{max}$ . The value of M that is closest to an integer value may be selected, as this represents the mostly likely solution to Equation 6, and thus the most likely actual thickness. Then the initial thickness may be calculated from Equation 6 or 7.

Of course, a value of N could be calculated for each integer value of M, in which case the maximum value,  $M_{max}$ , of M would be equal to  $D_{max}/\Delta D_1$ . However, it may be preferable to calculate for each integer value of the variable that is associated with the longer wavelength, as this will require fewer computations of the other integer variable.

Referring to FIGS. 8A and 8B, two hypothetical model functions 140 and 150 were generated to represent the polishing of a silicon oxide ( $SiO_2$ ) surface layer on a silicon wafer. The fitting coefficients that represent the hypothetical model

functions 140 and 150 are given in Table 1.

phase offset	$\phi_1 = 12.5 \text{ s}$	$\phi_2 = 65.5 \text{ s}$
peak-to-peak period	$\Delta T_1 = 197.5 \text{ s}$	$\Delta T_2 = 233.5 \text{ s}$

Table 1

These fitting coefficients were calculated for polishing rate of  $10 \text{ \AA/sec}$  and utilizing the polishing parameters in Table 2.

	1st optical system	2nd optical system
material	silicon oxide	silicon oxide
initial thickness	$10000 \text{ \AA}$	$10000 \text{ \AA}$
polishing rate	$10 \text{ \AA/sec}$	$10 \text{ \AA/sec}$
refractive index	$n_{\text{layer}} = 1.46$	$n_{\text{layer}} = 1.46$
wavelength	$\lambda_1 = 5663 \text{ \AA}$	$\lambda_2 = 6700 \text{ \AA}$
incidence angle in air	$\alpha_1 = 16^\circ$	$\alpha_2 = 16^\circ$
angle in layer	$\alpha_1' = 10.88^\circ$	$\alpha_2' = 10.88^\circ$
peak-to-peak thickness	$\Delta D_1 = 1970 \text{ \AA}$	$\Delta D_2 = 2336 \text{ \AA}$

Table 2

Using Equation 8, the M-values can be calculated for integer values of N, as shown in Table 3.

N	M	integer of M	thickness for N	thickness for M	thickness difference
0	0.27	0	655	125	530
1	1.45	1	2992	2100	892
2	2.63	3	5329	6050	-721
3	3.82	4	7665	8025	-360
4	<b>5.00</b>	<b>5</b>	<b>10002</b>	<b>9999</b>	<b>2</b>
5	6.18	6	12338	11974	364
6	7.37	7	14675	13949	725

7	8.55	9	17011	17899	-888
8	9.73	10	19348	19874	-526
9	10.92	11	21684	21849	-165
10	12.10	12	24021	23824	197
11	13.28	13	26357	25799	559
12	14.47	14	28694	27774	920
13	15.65	16	31030	31723	-693
14	16.83	17	33367	33698	-331
15	<b>18.02</b>	<b>18</b>	<b>35704</b>	<b>35673</b>	<b>30</b>
16	19.20	19	38040	37648	392
17	20.38	20	40377	39623	754
18	21.56	22	42713	43573	-860

Table 3

As shown, the best fit, i.e., the choice of N that provides a value of M that is closest to an integer, is for N=4 and M=5, with a resulting initial thickness of approximately 10000 Å, which is acceptable because  $t_i$  is less than the maximum thickness. The next best fit is N=15 and M=18, with a resulting initial thickness of approximately 35700 Å. Since this thickness is greater than the expected maximum initial thickness  $D_{\max}$  of 25000 Å, this solution may be rejected.

Thus, the invention provides a method of determining the initial thickness of a surface layer on a substrate during a CMP process. From this initial thickness value, the current thickness  $D(t)$  can be calculated as follows:

$$D(t) = D_{\text{initial}} - D_{\text{removed}}(t) \quad (12)$$

As a normal thickness for a deposited layer typically is between 1000Å and 20000Å, the initial as well as the current thickness can be calculated. The only prerequisite to estimate the actual thickness is to have sufficient intensity measurements to accurately calculate the peak-to-peak periods and phase offsets. In general, this requires at least a minima and a maxima for each of the wavelengths. However, the more minima and



maxima in the reflective trace, and the more intensity measurements, the more accurate the calculation of the actual thickness will be.

Some combinations of wavelengths may be inappropriate for in-situ calculations, for example, where one wavelength is a multiple of the other wavelength. A good combination of wavelengths will result in an "odd" relationship, i.e., the ratio of  $\lambda_1/\lambda_2$  should not be substantially equal to a ratio of small integers. Where the ratio of  $\lambda_1/\lambda_2$  is substantially equal to a ratio of small integers, there may be multiple integer solutions for N and M in Equation 8. In short, the wavelengths  $\lambda_1$  and  $\lambda_2$  should be selected so that there is only one solution to Equation 8 that provides substantially integer values to both N and M within the maximum initial thickness.

In addition, preferred combinations of wavelengths should be capable of operating in a variety of dielectric layers, such as  $\text{SiO}_2$ ,  $\text{Si}_3\text{N}_4$ , and the like. Longer wavelengths may be preferable when thick layers have to be polished, as less peaks will appear. Short wavelengths are more appropriate when only minimal polishing is performed.

The two optical systems 64, 84 can be configured with light sources having different wavelengths and the same propagation angle. Also, light sources 66, 86 could have different wavelengths and different respective propagation angles  $\alpha_1$ ,  $\alpha_2$ . It is also possible for light sources 66, 86 to have the same wavelength and different respective propagation angles  $\alpha_1$ ,  $\alpha_2$ .

The available wavelengths may be limited by the types of lasers, light emitting diodes (LEDs), or other light sources that can be incorporated into an optical system for a polishing platen at a reasonable cost. In some situations, it may impractical to use light sources with an optimal wavelength relationship. The system may still be optimized, particularly when two off-axis optical systems are used, by using different angles of incidence for the light beams from the two sources. This can be seen by from the expression for the peak-to-peak thickness  $\Delta D$ ,

$\Delta D = \lambda / (2n \cdot \cos \alpha')$ , where  $\lambda$  is the wavelength of the light source,  $n$  is the index of refraction of the dielectric layer, and  $\alpha'$  is the propagation angle of the light through the layer in the thin film structure. Thus, an effective wavelength  $\lambda_{eff}$  can be defined as  $\lambda / \cos \alpha'$ , and it is the effective wavelength  $\lambda_{eff}$  of each light source that is important to consider when optimizing the wavelengths of the different light sources. However, one effective wavelength should not be an integer multiple of the other effective wavelength, and the ratio of  $\lambda_{eff1} / \lambda_{eff2}$  should not be substantially equal to a ratio of small integers.

Referring to FIGS. 9 and 10, CMP apparatus 20a has a platen 24 configured similarly to that described above with reference to FIGS. 1 and 2. CMP apparatus 20a, however, includes an off-axis optical system 64 and a normal-axis optical system 84a. The normal axis optical system 84a includes a light source 86a, a transreflective surface 91, such as a beam splitter, and a detector 88a. A portion of light beam 90a passes through beam splitter 91, and propagates through transparent window 82a and slurry 36a to impinge substrate 10 at normal incidence. In this implementation, the aperture 80a in platen 24 can be smaller because light beam 90a passes through the aperture and returns along the same path.

Referring now to FIG. 11, in another implementation, CMP apparatus 20b has a single opening 60b in platen 24b and a single window 62b in polishing pad 30b. An off-axis optical system 64b and a normal-axis optical system 84b each direct respective light beams through the same window 62b. The light beams 70b and 90b may be directed at the same spot on substrate 10. This implementation needs only a single optical interrupter 162. Mirrors 93 may be used to adjust the incidence angle of the laser on the substrate.

Referring now to FIG. 12, in yet another implementation, CMP apparatus 20c has two off-axis optical systems 64c and 84c that direct light beams 70c and 90c at the same spot on substrate 10. Light source 66c and detector 68c of optical system 64c and light

source 86c and detector 88c of optical system 84c may be arranged such that a plane defined by light beams 70c and 72c crosses a plane defined by light beams 90c and 92c. For example, optical systems 64c, 84c can be offset by about 90° from each other.

5 This implementation also needs only a single optical interrupter 162, and permits the effective wavelength of the first light beam 70c to be adjusted by modifying the incidence angle.

Although the optical systems 64c, 84c are illustrated as using different propagation angles  $\alpha_1$  and  $\alpha_2$ , the propagation  
10 angles can be the same. In addition, the light sources could be located side by side (horizontally), the light beams could reflect off a single mirror (not shown), and the return beams could impinge two areas of a single detector. This would be conducive to combining the two light sources, mirror and detector in a single optical module. Furthermore, the light beams could  
15 impinge different spots on the substrate.

In another implementation, shown in FIG. 13, two optical systems 64d, 84d are arranged next to each other in separate modules. Optical systems 64d, 84d have respective light sources  
20 66d, 86d, detectors 68d, 88d, and mirrors 73d and 93d to direct the light beams onto the substrate at the described propagation angles  $\alpha_1$  and  $\alpha_2$ .

It will be understood that other combinations of optical systems and window arrangements are also within the scope of the invention, as long as the optical systems operate at different  
25 effective wavelengths. For example, different combinations of off-axis optical systems and normal-axis optical systems can be arranged to direct light beams through either the same or different windows in the platen. Additional optical components  
30 such as mirrors can be used to adjust the propagation angles of the light beams before they impinge the substrate.

Rather than a laser, a light emitting diode (LED) can be used as a light source to generate an interference signal. The important parameter in choosing a light source is the coherence  
35 length of the light beam, which should be on the order of or

greater than twice the optical path length of the light beam through of the polished layer. The optical path length OPL is given by

$$OPL = \frac{2d \cdot n_{layer}}{\cos \alpha'} \quad (13)$$

where d is the thickness of the layer in structure 14. In general, the longer the coherence length, the stronger the signal will be. Similarly, the thinner the layer, the stronger the signal. Consequently, as the substrate is polished, the interference signal should become progressively stronger. As shown in FIGS. 14 and 15, the light beam generated by an LED has a sufficiently long coherence length to provide a useful reflectance trace. The traces in FIGS. 14 and 15 were generated using an LED with a peak emission at 470nm. The reflectance traces also show that the interference signal becomes stronger as the substrate is polished. The availability of LEDs as light sources for interference measurements permits the use of shorter wavelengths (e.g., in the blue and green region of the spectrum) and thus more accurate determination of the thickness and polishing rate. The usefulness of an LED for this thickness measurement may be surprising, given that lasers are typically used for interferometric measurements and that LEDs have short coherence lengths compared to lasers.

Because the apparatus of the invention uses more than one optical system operating at more than one effective wavelength, two independent end point signals can be obtained. The two end point signals can be cross-checked when used, for example, to stop the polishing process. This provides improved reliability over systems having only one optical system. Also, if only one end point comes up and if within a predetermined time the other end point does not appear, then this can be used as a condition to stop the polishing process. In this way, a combination of both end point signals, or only one end point signal may be used

as a sufficient condition to stop the polishing process.

Before the end point appears, signal traces from different optical systems may be compared with each other to detect irregular performance of one or the other signal.

5 When the substrater has an initially irregular surface topography to be planarized, the reflectance signal may become cyclical after the substrate surface has become significantly smoothed. In this case, an initial thickness may be calculated at an arbitrary time beginning once the reflectance signal has  
10 become sinusoidal. In addition, an endpoint (or some other process control point) may be determined by detecting a first or subsequent cycle, or by detecting some other predetermined signature of the interference signal. Thus, the thickness can be determined once an irregular surface begins to become planarized.

5 The invention has been described in the context of a blank wafer. However, in some cases it may be possible to measure the thickness of a layer overlying a patterned structure by filtering the data signal. This filtering process is also discussed in the above-mentioned U.S. Patent Application Serial No. 08/689,930.

20 In addition, although the substrate has been described in the context of a silicon wafer with a single oxide layer, the interference process would also work with other substrates and other layers, and with multiple layers in the thin film structure. The key is that the surface of the thin film  
25 structure partially reflects and partially transmits, and the underlying layer or layers in the thin film structure or the wafer at least partially reflect, the impinging beam.

The present invention has been described in terms of a preferred embodiment. The invention, however, is not limited to  
30 the embodiment depicted and described. Rather, the scope of the invention is defined by the appended claims.

What is claimed is: